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Association between transportation noise and blood pressure in adults living in multi-storey residential buildings

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ABSTRACT

Epidemiological studies have demonstrated that transportation noise is associated with blood pressure and hypertension, but little is known about its relationship in the adults living in multi-storey residential buildings, where neighbour noise is frequently heard. This study aimed to investigate the effects of transportation noise exposure on blood pressure in 400 adult residents of multi-storey residential buildings and modifying effects of indoor noise annoyance and self-rated noise sensitivity on the associations between transportation noise and blood pressure. Noise levels were measured on the top of buildings for 24 h, and levels of each house unit were then predicted for different sources and periods using noise maps. Adjusted linear regression analyses were performed to estimate the associations of noise exposure levels (L_{DEN}, L_{Day}, and L_{Night}) with systolic blood pressure (SBP) and diastolic blood pressure (DBP). The questionnaire also included questions related to annoyance caused by indoor noise, noise sensitivity, and sociodemographic variables. Adjusted regression models yielded significant effect estimates for a 5-dBA increase in overall transportation noise for 24 h (SBP $\beta = 0.20$; 95% confidence interval (CI): 0.25–1.81; DBP $\beta = 0.16$; 95% CI: 0.12–0.93). The overall (road traffic and railway noise) and road traffic noises showed stronger associations with the SBP than with the DBP, while the railway noise had similar associations with the SBP and the DBP. Stronger associations were estimated for the participants who reported higher indoor noise annoyance ratings. Furthermore, the regression coefficients between the noise exposure and blood pressure slightly increased ($\beta = 0.26$ and 0.22 for overall and road traffic noise, respectively for SBP) in a subgroup that excluded participants exposed to high railway noise. The results lend some support to the hypothesis that long-term exposure to transportation noise is associated with a higher blood pressure in adults living in multi-storey residential buildings.

1. Introduction

Noise negatively affects human health and well-being, and there have been growing concerns regarding noise-related health issues. According to the WHO (2011), at least 100 million people in the European Union (EU) are affected by road traffic noise and at least 1.6 million healthy years of life are lost due to road traffic noise in Western Europe. Recently, the WHO (2018) developed new environmental noise guidelines for the European region based on the evidences associating noise exposure with health outcomes such as annoyance, sleep disturbance and cardiovascular disease.

High blood pressure and hypertension have been considered as the leading risk factor for cardiovascular mortality. Thus, the association between environmental noise and cardiovascular disease have been explored in terms of blood pressure and hypertension. van Kempen et al. (2018) recently conducted a systematic review on the effect of noise on hypertension based on 40 previous studies (e.g., Chang et al., 2014; Foraster et al., 2014; Jarup et al., 2007). They reported positive associations between noise from air, road, or rail traffic and hypertension in the cross-sectional studies. In particular, a relative risk per 10 dB for the association between road traffic noise and prevalence of hypertension was 1.05 (95% confidence interval (CI): 1.02–1.08). By contrast, the results of two cohort studies (Sørensen et al., 2012; Sørensen et al., 2011) did not show an increased risk of hypertension in individuals exposed to traffic noise. The reason for this inconsistent finding, however, remains unclear; thus, further studies are warranted to clarify the relationship between transportation noise and risk for cardiovascular disease.

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Table 1
Characteristics of the study sample.

Characteristics		Site 1 (n = 100)	Site 2 (n = 100)	Site 3 (n = 100)	Site 4 (n = 100)
Gender (n)					
Male		45	46	56	47
Female		55	54	44	53
Age (mean ± *SD*)		44.3 ± 9.6	41.6 ± 11.2	42.5 ± 10.5	43.4 ± 10.6
Education (n)					
High school		17	22	13	21
College/University		80	65	74	74
Postgraduate or above		3	13	13	5
Occupation (n)					
Full-time		64	54	45	43
Part-time		14	10	21	13
Self-employed		5	5	11	7
Student		6	16	9	4
Homemaker		11	15	11	32
Unwaged/retired		0	0	3	0
Other		0	0	0	1
Annual household income (n)					
Less than £13,327		1	0	2	0
Between £13,327 and £19,993		10	1	16	11
Between £19,993 and £26,660		20	3	26	17
Between £26,660 and £33,327		35	7	33	36
Between £33,327 and £39,993		24	35	18	27
Higher than £39,993		10	54	5	9
Length of residence (in months; mean ± *SD*)		141.1 ± 78.3	107.6 ± 42.5	59.2 ± 29.0	33.7 ± 7.4
Window orientation (n)					
Directly facing the street		21	34	30	6
Not directly facing the street		79	66	70	94
Blood pressure (mmHg) (mean ± *SD*)					
Systolic blood pressure		118.9 ± 10.1	121.4 ± 10.4	117.6 ± 13.4	111.2 ± 10.8
Diastolic blood pressure		77.3 ± 8.0	78.4 ± 7.2	76.4 ± 8.7	75.4 ± 6.5
Noise sensitivity (mean ± *SD*)		78.7 ± 11.7	79.6 ± 11.0	79.3 ± 15.6	80.3 ± 14.6
Total annoyance (mean ± *SD*)		4.5 ± 1.8	6.3 ± 1.9	4.7 ± 2.1	2.5 ± 1.4
Road traffic noise annoyance (mean ± *SD*)		4.3 ± 2.2	5.4 ± 2.5	1.8 ± 1.3	1.1 ± 1.0
Railway noise annoyance (mean ± *SD*)		2.3 ± 3.0	5.3 ± 2.7	6.0 ± 2.3	–
Indoor noise	Dominant source (n)				
	Footsteps: children	32	53	37	32
	Footsteps: adults	26	18	26	30
	Furniture scraping	10	15	12	12
	Dropped items	15	10	11	14
	Door banging	15	0	6	4
	Plumbing system	2	4	8	8
	Child(ren) living upstairs (n)				
	Yes	50	61	59	48
	No	35	24	27	28
	Don't know	15	15	14	24
	Time of major noise exposure (n)				
	06:00–09:00	41	32	18	23
	09:00–12:00	3	2	7	6
	12:00–18:00	4	2	4	3
	18:00–20:00	10	2	16	8
	20:00–06:00	42	62	55	60
	Indoor noise annoyance (mean ± *SD*)	4.5 ± 3.4	4.0 ± 2.5	4.1 ± 2.8	3.4 ± 2.6
Information of each site	Construction year	1994	2002	2009	2014
	Number of buildings	21	7	7	8
	Number of residences	1827	583	262	522
	Highest floor level	25th	23rd	15th	18th
	Slab thickness (mm)	150	150	210	180
	Floor area (i.e. residence size) (m^2)	58–85	84	107–157	52–60

Majority of previous studies on noise and cardiovascular disease were conducted in Western countries mainly in the EU. According to the recent housing statistics of EU (Eurostat, 2018), more than half of the population in EU live in detached houses and semi-detached or terraced houses. Therefore, most participants of previous studies might have lived in houses where neighbours' noise was rarely heard. On the contrary, the proportion of multi-story residential buildings has been growing all over the world (Liu et al., 2015). For example, most common housing type in Korea are multi-storey residential buildings and apartment complexes, in particular in urban areas where transportation noise is problematic. Residents in multi-storey residential buildings are frequently exposed to noise from their neighbours. In particular, noise produced by human walking or running has been a major cause of noise complaints (Park and Lee, 2019). Consequently, the behaviour and health of residents in multi-storey residential buildings could be affected by indoor as well as outdoor noise. However, there is still lack of evidence on the impact of transportation noise on blood pressure from residents of this multi-storey residential buildings and the modifying effects of indoor noise and attitudinal variables (e.g., noise sensitivity) on the associations between outdoor noise and blood pressure.

Hence, this study aimed to investigate the effects of transportation noise on blood pressure in adults who had lived in multi-storey residential buildings. It was also hypothesised that indoor noise annoyance and self-rated noise sensitivity might modify the associations between transportation noise and blood pressures. A total of 400 adults were recruited from four apartment complexes to measure their blood pressures. Meanwhile, participants were asked to rate their annoyance caused by indoor noise and noise sensitivity. In addition, outdoor noise levels were measured, and noise mappings were then developed to predict noise exposure level of each participant.

2. Materials and methods

2.1. Study sample

The sample of this study was recruited from four apartment complexes in the Gyeonggi province of South Korea with 100 residents from each complex (N = 400). The oldest complex was built in 1994 and the newest in 2014. Each complex (site) consists of 7–21 multi-storey residential buildings with 15–25 floors. Windows in all the residences were double glazed, which resulted in nearly identical window insulation performances. The thickness of the slab ranged from 150 to 210 mm. The smallest residence floor area was 52 m^2 and the largest 157 m^2. All the sites were located in the vicinity of traffic roads; Sites 1 and 2 were in nearby roads with three or more lanes, while Sites 3 and 4 were close to roads with a smaller number of (e.g., one or two) lanes. In addition, Sites 1, 2, and 3 were exposed to additional railway noise. Healthy residents aged between 20 and 60 years were recruited. Residents taking antihypertensive medications, with abnormal body mass index, and with any cardiovascular disease, respiratory disease (asthma), diabetes mellitus, epilepsy, hearing loss, and musculoskeletal disorder were excluded. The participants took part in the study individually. Each participant was invited to visit the designated place ('study area') in each site to take part in the study. The study area was located near the management office building at each site (e.g., a meeting room), which enabled the participants to easily access the location. A participant information sheet and written consent form were provided to the participant upon arrival. The purpose of the study was clearly explained prior to obtaining consent and the participant was assured of complete anonymity. The participant's blood pressure was then measured and they were requested to complete the questionnaire. This study was approved by the Ethical Committee of the School of the Arts, University of Liverpool. All data were collected in a manner consistent with the ethical standards for the treatment of human participants. Mean ages of the participants varied from 41.6 to 44.3 years across the sites, and the majority of participants graduated from college or university. More than half of the participants were working either full-time or part-time. Most participants reported that their annual household income ranged between £26,660 and £33,327. The longest average length of residence in the current house was observed at Site 1 (141 months = 11 years and 9 months) and the shortest was at Site 4 (34 months = 2 years and 10 months). In addition, more than half of the participants reported that the windows of their houses did not directly face the street. Details of the participants and each site can be found in Table 1.

2.2. Outdoor noise measurements and predictions

Outdoor noise levels were measured for 24 h using sound level meters (SVAN 943, Svantek) on top of 18 buildings. There were a total of 43 buildings in four apartment complexes, of which 18 buildings were selected for the noise measurements based on the number of buildings and noise source locations. Seven buildings were chosen at Site 1, which has the most buildings, whereas three or four buildings were selected at the other sites. The locations of the selected buildings were evenly distributed across the apartment complexes including the closest and farthest buildings from the noise sources. The sound level meter was positioned 1.2 m above the rooftop of each building. The A-weighted equivalent sound pressure levels with fast time weighting were recorded every one minute ($L_{\mathrm{Aeq,1\text{-}min}}$) in the range of 30–130 dBA. Measurement ranges of the sound level meter were set up based on the maximum noise level at each building. From the 24-h noise recordings, L_{DEN} (day-evening-night noise levels) were calculated. A penalty of 5 dB was added from 19:00 to 22:00, and a penalty of 10 dB was added from 22:00 to 07:00 to derive L_{DEN}. In addition, L_{Day} (noise level from 06:00 to 22:00) and L_{Night} (noise level from 22:00 to 06:00) were computed. Noise maps were then created using SoundPLAN software (version 7.4), based on the data collected from the noise measurements and measured traffic flow from the Korean Government (http://viewt.ktdb.go.kr). The predicted L_{DEN} from the noise maps showed good agreement with the measured noise levels within 3 dB. The maximum difference between the predicted and measured noise levels was 2.2 dB and the root mean squared error (RMSE) was 1.2 dB. The correlation coefficients between the measured and predicted noise exposure levels were also > 0.95. This indicates that the noise maps can reliably predict the noise levels at different locations. Thus, the overall noise level of each housing unit was predicted by placing the receivers at the building facades. In addition, noise levels (L_{DEN}, L_{Day}, and L_{Night}) of the road traffic and railway noise were separately predicted to investigate the impacts of individual noise sources on the blood pressure for Sites 1–3. Only the levels of the road traffic noise were predicted for Site 4 as there was no railway near this site. Considering all the noise sources, 28.3% of the participants were exposed to transportation noise above 60 dB (L_{DEN}), while 52.5% were exposed to noise below 50 dB.

2.3. Questionnaire

The questionnaire consisted of two parts. The first part comprised general socio-demographic information such as age, gender, annual household income, education, employment, floor level, length of residence, and noise sensitivity. For noise sensitivity, the questionnaire included 21 questions, whose answers were scored using the Weinstein's Noise Sensitivity Scale (Weinstein, 1978). In the second part of the questionnaire, participants were asked to rate their level of annoyance caused by outdoor and indoor noise on a 11-point scale (0 = *'not at all'* and 10 = *'extremely'*) according to the following instruction: 'Thinking about the last 12 months, when you are here at home, how much does noise from outside (neighbours) annoy you'.

2.4. Blood pressure measurement

The blood pressure of each participant was measured by the trained interviewer within the management office buildings only in the afternoon. The measurements were conducted over several days at each site until 100 participants were recorded. Blood pressure was measured using a portable, non-invasive, automated monitoring system (Omron M3 Comfort, HEM-7134-E). Following participant consent in the study, the blood pressure measurement was performed after a 15-min rest period in a sitting position, with the right arm at the heart level. Any tight-fitting or thick clothing was removed from the arm before measurement. Two measurements were conducted with a 5-min interval. If the difference between measurements exceeded 5 mmHg, the third measurements were performed and mean values of systolic and diastolic pressures (SBP and DBP) were calculated.

2.5. Statistical analysis

Statistical analyses were conducted using the variables listed in Table 1 and the predicted outdoor noise levels. A few of the variables in Table 1 were not used in the analyses as they were listed in the table only to describe each site (e.g., the number of buildings or residences). Moreover, the floor levels of the participants' residences and distance from major traffic roads or railways were not included in the analyses as they had already been included in the predicted noise exposure levels of each housing unit. The data were analysed using SPSS for Windows

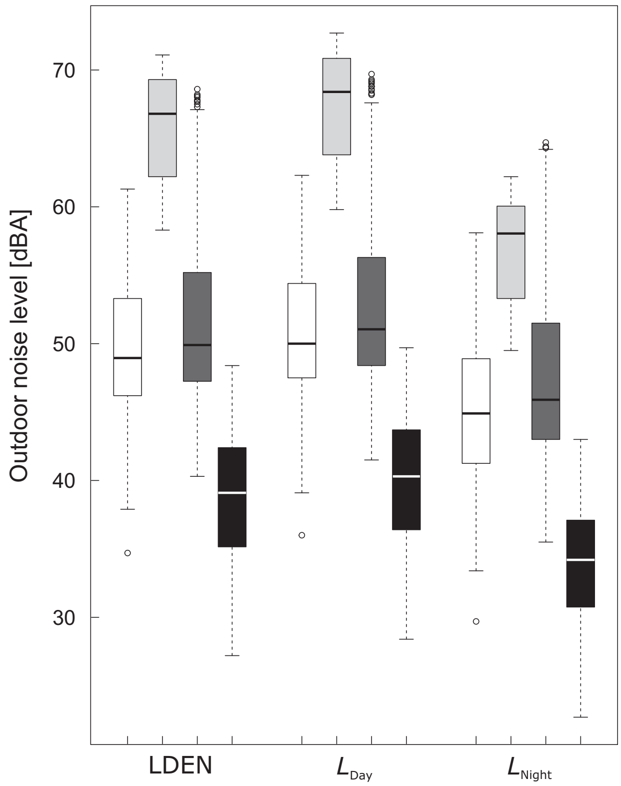

Fig. 1. Boxplots of the A-weighted equivalent sound pressure levels at each site in terms of the L_{DEN}, L_{Day}, and L_{Night} (white: Site 1, bright grey: Site 2, dark grey: Site 3, and black: Site 4).

(version 22.0, SPSS Inc. Chicago, IL). Correlations between the variables (e.g., annoyance and blood pressure) were assessed using Spearman's rank correlation coefficients. Differences between the groups (e.g., sensitive and less sensitive groups) were tested using the independent samples *t*-tests and Mann Whitney *U* tests for parametric and nonparametric data, respectively. Variables significantly related to the systolic and diastolic blood pressures were included in the multiple linear regression models based on the results from the univariate analyses. The present study considered *p* values of < 5% ($p < 0.05$) as statistically significant.

3. Results

Fig. 1 shows the boxplots of the overall noise levels at each site in terms of the L_{DEN}, L_{Day}, and L_{Night}. The central bar in each box is the median, while the solid boxes and the whiskers indicate the interquartile range and the 5th to the 95th percentiles, respectively. The highest noise levels were shown at Site 2, followed by Sites 3, 1, and 4. In particular, the noise levels of Site 4 were significantly lower than those of other sites because it was exposed to only one traffic road with two lanes and less traffic.

Spearman's correlation coefficients of the blood pressure using the evaluated variables are listed in Table 2. First, age had an inverse correlation with the DBP, while the length of residence had a positive correlation with the SBP. House ownership and self-reported noise sensitivity showed significant correlations with both the SBP and DBP. Second, the SBP had significant correlations with all the dwelling characteristics, while the DBP had a significant correlation with all features except the house size and window orientation. Third, the indoor noise characteristics only presented significant correlations between the SBP and slab thickness and noise source. However, the self-reported indoor noise annoyance had significant and strong correlations with both the SBP and DBP. Fourth, all the outdoor noise levels and self-reported annoyance ratings with respect to the outdoor noise had significant correlations with the blood pressure. Given that the self-reported ratings (i.e. noise sensitivity and annoyance ratings) showed strong correlation coefficients with the blood pressure, participants who were more sensitive to noise or perceived indoor or outdoor noise as more annoying were more likely to have/experience higher diastolic and systolic blood pressures.

Table 2
Spearman's correlation coefficients of blood pressure with the tested variables (**$p < 0.01$ and *$p < 0.05$).

	SBP	DBP
Personal characteristics		
Age	−0.052	−0.101*
Gender	0.050	0.034
Length of residence (in months)	0.133**	0.094
Education	0.058	−0.039
Occupation	−0.067	−0.007
Annual household income	0.079	0.058
House ownership	−0.251**	−0.143**
Self-reported noise sensitivity	0.781**	0.775**
Dwelling characteristics		
Building age (in months)	0.237**	0.115*
Floor of the house	0.104*	0.115*
Floor area (i.e. residence size) (m^2)	0.179**	0.085
Window orientation	−0.102*	−0.053
Distance from the traffic road (m)	−0.195**	−0.115*
Distance from the railway (m)	−0.175**	−0.167**
Indoor noise		
Slab thickness (mm)	−0.122*	−0.091
Child(ren) upstairs	0.029	0.062
Noise source	−0.102*	−0.081
Time of noise	−0.010	0.013
Self-reported indoor noise annoyance	0.748**	0.732**
Outdoor noise		
Overall_L_{DEN}	0.305**	0.177**
Overall_L_{Day}	0.314**	0.183**
Overall_L_{Night}	0.312**	0.191**
RTN_L_{DEN}	0.239**	0.140**
RTN_L_{Day}	0.258**	0.152**
RTN_L_{Night}	0.258**	0.164**
RN_L_{DEN}	0.194**	0.167**
RN_L_{Day}	0.166**	0.152**
RN_L_{Night}	0.176**	0.144*
Self-reported total annoyance	0.726**	0.611**
Self-reported RTN annoyance	0.547**	0.483**
Self-reported RN annoyance	0.542**	0.431**

Table 3 indicates the associations between noise exposures and blood pressures obtained from the regression analysis. A 5-dB increase in all noise sources (overall, road traffic, and railway) and noise exposures (L_{DEN}, L_{Day}, and L_{Night}) were significantly associated with blood pressure measurements. Overall and road traffic noise had stronger associations with SBP than with DBP. For example, the standardised regression coefficients (β) of overall noise level for 24 h (L_{DEN}) was 0.20 with 95% confidence interval (CI) of 0.25–1.81 for SBP and 0.16 with 95% CI of 0.12–0.93 for DBP. Railway noise, however, showed similar associations with both SBP and DBP. For instance, the β of overall noise level for 24 h (L_{DEN}) for SBP was 0.26 with 95% CI of 0.70–2.29, while that for DBP was 0.25 with 95% CI of 0.48–1.52. It was also found that railway noise showed stronger relationships with blood pressures than overall and road traffic noise. The maximum β of overall noise was 0.21 for SBP, whereas railway noise's maximum β was 0.26 for SBP. Furthermore, the associations between noise exposures and blood pressures were quite similar across noise exposures (L_{DEN}, L_{Day}, and L_{Night}) for both SBP and DBP. Therefore, only L_{DEN} was used for the following analyses concerning noise exposure and blood pressures.

Two variables were considered as effect modifiers affecting the associations between noise exposure and blood pressure: 1) indoor noise annoyance and 2) noise sensitivity. In order to investigate the impacts

Table 3
Association between blood pressure and noise levels; estimated changes in blood pressure (mmHg) for a 5-dBA increment in noise level.

	SBP[a]				DBP[b]			
	β/5 dBA	95% CI		*p*-Value	β/5 dBA	95% CI		*p*-Value
Overall noise								
L_{DEN}	0.20	0.25	1.81	0.01	0.16	0.12	0.93	0.01
L_{Day}	0.21	0.31	1.88	0.01	0.16	0.14	0.94	0.01
L_{Night}	0.17	0.13	1.78	0.02	0.15	0.12	1.03	0.01
Road traffic noise								
L_{DEN}	0.17	0.03	1.71	0.04	0.13	0.04	0.79	0.03
L_{Day}	0.20	0.15	1.82	0.02	0.13	0.05	0.80	0.03
L_{Night}	0.18	0.12	2.00	0.03	0.15	0.12	1.00	0.01
Railway noise								
L_{DEN}	0.26	0.70	2.29	0.00	0.25	0.48	1.52	0.00
L_{Day}	0.24	0.58	2.19	0.00	0.23	0.43	1.46	0.00
L_{Night}	0.25	0.65	2.29	0.00	0.23	0.40	1.46	0.00

[a] The models for testing SBP were adjusted for length of residence, house ownership, building age, slab thickness, and size of the house.

[b] The models for testing DBP were adjusted for house ownership and building age.

of modifiers, participants were divided into two groups according to their annoyance ratings and noise sensitivity scores. The mean indoor noise annoyance rating (0 − 10) was 4.0 (*SD* = 2.9) and the mean noise sensitivity score (1–126) was 79.3 (*SD* = 13.3). The mean values were used as cut-off points to classify the participants. Participants whose indoor noise annoyance ratings were ≤4.0 were classified as the low noise annoyance group (*N* = 227), while those with noise annoyance ratings > 4.0 were classified as the high noise annoyance group (*N* = 173). Participants whose noise sensitivity scores were ≤79.3 were classified as the low noise sensitivity group (*N* = 204), while those with noise sensitivity scores > 79.3 were classified as the high noise sensitivity group (*N* = 196).

Fig. 2 presents the boxplots of blood pressures for low and high indoor noise annoyance groups. For both SBP and DBP, the high noise annoyance group showed greater blood pressures. Independent *t*-test confirmed that the blood pressures of the high noise annoyance group were significantly greater than those of the low noise annoyance group ($t(374.9) = -21.04$, $p < 0.01$ for SBP and $t(196.9) = -19.76$, $p < 0.01$ for DBP). The modifying effects of indoor noise annoyance on the associations between noise exposure and blood pressure are listed in Table 4. For overall and road traffic noise, the high noise annoyance group showed stronger association between a 5-dB increase and blood pressure than the low noise annoyance groups. However, the differences between the groups were little for the railway noise. With regard to overall and road traffic noise, high annoyance groups showed greater regression coefficients than low annoyance groups for both SBP and DBP. However, in the low annoyance group, most associations between noise exposure and blood pressure were not significant. Railway noise showed a similar tendency but only the associations with SBP were significant.

The boxplots of blood pressure for low and high noise sensitivity groups are presented in Fig. 3. Greater blood pressures were observed from the high noise sensitivity group, and the differences between the groups were statistically significant ($t(356.7) = -16.77$, $p < 0.01$ for SBP and $t(378.0) = -19.48$, $p < 0.01$ for DBP). Table 5 shows the associations between noise exposure and blood pressure for low and high noise sensitivity groups. For overall noise and road traffic noise, noise-sensitive groups had stronger associations between a 5-dB increase and blood pressure, whereas no significant association was found for railway noise.

About 77 participants who were exposed to higher railway noise level than road traffic noise level were excluded to focus on the impact of road traffic noise on blood pressure. As listed in Table 6, the exclusion of participants exposed to relatively high railway noise resulted in increases of regression coefficients indicating associations between noise exposure and blood pressure.

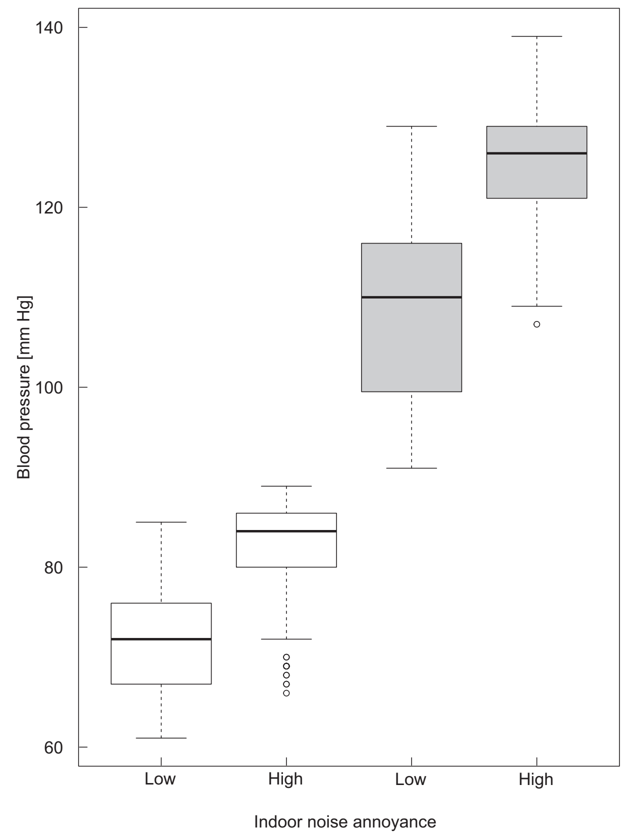

Fig. 2. Boxplots of SBP and DBP for low and high indoor noise annoyance groups (white: diastolic pressure and grey: systolic pressure).

4. Discussion

The present study revealed that both systolic and diastolic blood pressures increased with higher noise level periods of noise exposure (24 h, daytime, and nighttime). Overall, the results of this study are in agreement with those of previous studies (Belojević et al., 2008; Chang et al., 2009; Dratva et al., 2012; Haralabidis et al., 2008), which evaluated the association between transportation noise and blood pressure. However, the changes in SBP and DBP in this study were relatively smaller than those of previous studies. Foraster et al. (2014) reported that a 5-dBA increment in road traffic noise at nighttime (L_{night}) increased the SBP by 0.42 mmHg. In the present study, the increase of SBP per 5-dBA increment in road traffic noise (L_{night}) was 0.18 mmHg. The difference in the changes in SBP between the present study and the previous study (Foraster et al., 2014) might be due to the characteristics of the study samples. Only healthy adults without hypertension were recruited in the present study, whereas around half of the participants were diagnosed with hypertension in the previous study (Foraster et al., 2014). Similarly, the changes in SBP and DBP per 5-dBA increment in noise level (1.43 for SBP and 1.40 for DBP) reported by Chang et al. (2009) were greater than those reported in the present study conducted among 60 young adults without hypertension. This might be because Chang et al. (2009) have measured the personal noise exposure level using a dosimeter as opposed to noise estimation from a noise map in the present study. This finding suggests that the use of an estimated noise exposure level might underestimate the risk of blood pressure.

Compared with road traffic noise, only a few studies attempted to explore the association between railway noise and blood pressure. The

Table 4
Modifying effects of indoor noise annoyance (low and high) on the association between blood pressure and noise levels; estimated changes in blood pressure (mmHg) for a 5-dBA increment in noise level (**$p < 0.01$ and *$p < 0.05$).

L_{DEN}	SBP[a]				DBP[b]			
	β/5 dBA	95% CI		p-Value	β/5 dBA	95% CI		p-Value
Overall noise								
Low noise annoyance	0.13	−0.37	1.54	0.23	0.13	−0.13	0.82	0.15
High noise annoyance	0.39	0.49	1.54	0.00	0.28	0.24	0.92	0.00
Road traffic noise								
Low noise annoyance	0.09	−0.59	1.36	0.43	0.18	0.04	0.93	0.03
High noise annoyance	0.51	0.67	1.86	0.00	0.29	0.25	0.88	0.00
Railway noise								
Low noise annoyance	0.20	0.02	2.06	0.05	0.14	−0.15	1.11	0.13
High noise annoyance	0.22	0.11	1.11	0.02	0.15	−0.07	0.79	0.10

[a] The models for testing SBP were adjusted for length of residence, house ownership, building age, slab thickness, and size of the house.
[b] The models for testing DBP were adjusted for house ownership and building age.

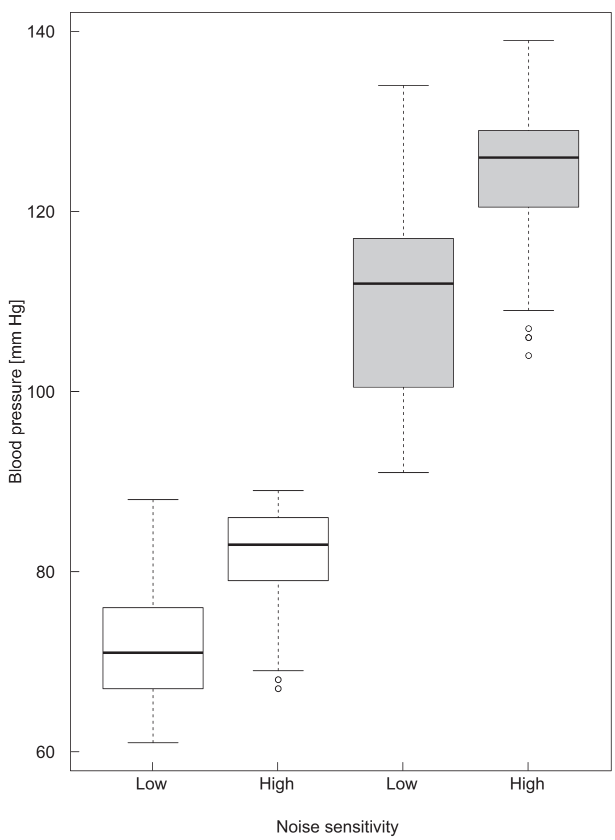

Fig. 3. Boxplots of SBP and DBP for low and high noise sensitivity groups (white: diastolic pressure and grey: systolic pressure).

present study yielded significant positive associations of railway noise within 24 h, during daytime, and during nighttime with SBP and DBP. This finding is in accordance with the results of a field study (Dratva et al., 2012) where SBP and DBP increased due to diurnal and nocturnal railway noise. However, the increases of SBP and DBP due to railway noise in the present study were smaller than those reported in a previous study (Dratva et al., 2012). This might be because road traffic noise was more dominant than railway noise in this study; thus, the number of participants exposed to louder railway noise was smaller than those exposed to road traffic noise. Sørensen et al. (2011) also highlighted the association between railway noise and risk for hypertension for noise level above 60 dB. In addition, Lercher et al. (2010) pointed out that the use of equivalent noise level underestimates the detrimental effect of non-stationary noise (e.g., railway and aircraft noise). Therefore, other noise measures such as maximum sound pressure level (L_{max}) could be used in future studies.

Neighbour noise has been a major noise source in multi-storey residential buildings, and its impact on psycho-physiological reactions have been widely reported (Park and Lee, 2017; Park et al., 2018b). In addition, noise sensitivity has been regarded as one of the attitudinal variables affecting people's reactions to noise (Miedema and Vos, 2003; Park et al., 2018a). Therefore, in the present study, indoor noise annoyance and noise sensitivity were introduced as modifiers affecting the association between noise exposure and blood pressure. It was revealed that noise-sensitive people and more annoyed participants due to indoor noise showed significantly higher SBP and DBP than others. The mean overall noise levels for 24 h for both groups (low and high annoyance groups; low and high noise sensitivity groups) were quite similar. For example, L_{DEN} for low and high noise sensitivity groups were 51.5 and 51.7 dB, respectively. This indicates that indoor noise annoyance and noise sensitivity were developed regardless of outdoor noise exposure level because the level and frequency of neighbour noise are mainly affected by neighbours' activities (Park et al., 2017). Foraster et al. (2014) also demonstrated stronger associations between indoor traffic noise during nighttime and hypertension with increasing traffic annoyance ratings. However, several studies (Lercher et al., 2011; Lercher et al., 2018) reported the opposite findings. For instance, Lercher et al. (2018) revealed that those who rated higher annoyance exhibited lower SBP as they had behavioural coping strategies to noise. Inconsistent findings in existing literature with regard to the effect of noise annoyance on the association between noise exposure and blood pressure might be due to the different environment conditions and research designs. Foraster et al. (2014) focused on indoor traffic noise during nighttime (L_{night}), whereas other previous studies (Lercher et al., 2011; Lercher et al., 2018) and the present study measured noise levels for 24 h. In addition, compared with other studies, all the participants of this study were residents who were exposed to neighbour noise.

Significant increases in SBP and DBP were observed when the source of the noise was taken into account. The effects of the source-specific noise (road traffic and railway noise) were similar to those of the total measured noise levels (overall). When 77 participants dominantly exposed to railway noise were excluded, the associations between road traffic noise and blood pressure slightly increased. This finding showed a good agreement with those of previous studies (Eriksson et al., 2007; Selander et al., 2009) on road traffic noise. Eriksson et al. (2007) reported a stronger association between aircraft noise and hypertension among participants not annoyed by other noise sources. Similarly, Selander et al. (2009) reported that the exclusion of participants exposed to railway noise increased the odds ratio of myocardial infarction. As Selander et al. (2009) already pointed out, this indicates that exposure misclassification could affect the associations

Table 5
Modifying effects of noise sensitivity (low and high) on the association between blood pressure and noise levels; estimated change of blood pressure (mmHg) for a 5-dBA increment in noise level (** $p < 0.01$ and * $p < 0.05$).

L_{DEN}	SBP[a]				DBP[b]			
	β/5 dBA	95% CI		p-Value	β/5 dBA	95% CI		p-Value
Overall noise								
Low noise sensitivity	0.18	−0.12	1.95	0.08	0.14	−0.08	0.89	0.10
High noise sensitivity	0.36	0.48	1.61	0.00	0.22	0.09	0.75	0.01
Road traffic noise								
Low noise sensitivity	0.10	−0.57	1.58	0.36	0.12	−0.10	0.79	0.13
High noise sensitivity	0.45	0.67	1.91	0.00	0.21	0.09	0.70	0.01
Railway noise								
Low noise sensitivity	0.19	−0.03	2.02	0.06	0.15	−0.11	1.14	0.10
High noise sensitivity	0.19	0.00	1.15	0.06	0.14	−0.11	0.79	0.14

[a] The models for testing SBP were adjusted for length of residence, house ownership, building age, slab thickness, and size of the house.
[b] The models for testing DBP were adjusted for house ownership and building age.

Table 6
Association between blood pressure and noise levels for a subgroup excluding participants exposed to higher railway noise level; estimated changes in blood pressure (mmHg) for a 5-dBA increment in noise level.

L_{DEN}	SBP[a]				DBP[b]			
	β/5 dBA	95% CI		p-Value	β/5 dBA	95% CI		p-Value
Overall noise	0.26	0.35	2.12	0.01	0.21	0.23	1.11	0.00
Road traffic noise	0.22	0.18	1.97	0.02	0.20	0.18	1.04	0.01

[a] The models for testing SBP were adjusted for length of residence, house ownership, building age, slab thickness, and size of the house.
[b] The models for testing DBP were adjusted for house ownership and building age.

for participants who are exposed to multiple noise sources.

There are some limitations in this study. Although the present study found that the levels of outdoor transportation had statistically significant impacts on the blood pressure, the size of these effects was not strong. The results showed that the outdoor noise level by itself cannot fully predict the blood pressure, thus, requiring the consideration of various other factors. The body mass index is one of the most well known risk factors used to predict the blood pressure (Bovet et al., 2002; Dyer and Elliott, 1989). Thus, in this study, we controlled this factor by only recruiting those participants whose body mass index was within the normal range (18.5–25 kg/m^2). However, a limitation of this study is that a few of the other risk factors (e.g., smoking, hyperlipidemia, regular exercise, eating habits, coffee, and alcohol consumption) were not examined, which may have played a significant role (Group, 1978; Klatsky et al., 1977; Nielsen and Andersen, 2003; Noordzij et al., 2005). Collection of data on risk factors required approval from the residents' self-governing body as well as the management office of each apartment complex. Unfortunately, the level and range of collectible data were different across the sites; thus, the number of risk factors considered in this project significantly reduced. In the future, it is necessary to recruit apartment complexes that are favourable to the collection of all the risk factors. Additionally, indoor noise levels, participants' complaints about the indoor noise, time spent at home, and the duration of exposure could be modifying factors that affect the relationship between the outdoor noise exposure and blood pressure. Thus, future studies might assess whether and how the impact of the outdoor noise level changes when a few more risk factors are collectively considered. Moreover, the present study recruited healthy residents without hypertension; thus, it was not able to investigate the association between noise exposure and the risk of hypertension. In addition, a relatively small sample size ($N = 400$) was used; in particular, the number of people exposed to dominant railway noise was < 100. Therefore, future research is required to solely investigate the association between railway noise using a large sample who is dominantly exposed to railway noise and should include a mixture of adults with and without hypertension. This study focused on the residents living in multi-storey residential buildings; hence, they were frequently exposed to neighbour noise that might cause a high level of annoyance. The finding of this study on the modifying effects of noise annoyance was inconsistent with those reported in other previous studies and house type might have affected the results. In future studies, multiple house types should be considered to validate the effects of noise annoyance on the association between transportation noise and blood pressure.

5. Conclusions

Evidence on the association between transportation noise and blood pressure, especially for residents in multi-storey residential buildings, were presented. Railway noise showed stronger associations with SBP and DBP than road traffic noise. In particular, the impacts of noise on blood pressures were elevated in the population, excluding those dominantly exposed to railway noise. However, further investigation is required to compare the effects of road traffic and railway noise. Modifying effects of indoor noise annoyance and noise sensitivity on the associations between noise exposure and blood pressures were clearly observed. The results underline the need to investigate vulnerable populations with hypertension because relatively small increases in SBP and DBP were observed in healthy adults in this study.

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